Project no. 723678

"The next Generation of Carbon for the Process Industry"

Coordination and Support Action

Theme [SPIRE 5] – Potential use of CO_2 and non-conventional fossil natural resources in Europe as feedstock for the process industry

Deliverable 4.4:

Key project results – Best practise examples

Due date of deliverable: 30 August 2018

Actual submission date: 20 October 2018

Start date of project: 1 September 2016 Duration: 24 months

Organisation name of lead contractor for this deliverable: Dechema e.V.

Table of Contents

Introduction

The process industries and other crude oil consuming sectors are heavily dependent on fossil inputs for both carbon feedstock and energy, with the consequential CO_2 emission problems and import dependency as a result. To be prepared for a future with significantly reduced emissions they are seeking alternative carbon sources to replace traditional fossil fuels. ***The objective of the CarbonNext project was to evaluate the potential use of CO_2/CO and non-conventional fossil natural resources as feedstock for the process industry in Europe.*** The work examined the existing and expected sources of CO_2 and CO as well as non-conventional fossil natural resources such as shale gas, tar sands, coal bed methane, gas to liquid, and coal to liquid technologies. Results of the project include the identification of value chains within processes and where industrial symbiosis can be valuable (chemistry, cement, steel, etc.). The CarbonNext project will inform, as a basis for decision-making, Europe's SME's, large industry and policymakers with an enhanced understanding of the impact and opportunities for new sources of carbon for the processing industry. CarbonNext primarily focused on new sources of carbon as a feedstock and secondarily the impact on energy availability, price and emissions.

The present report summarizes the most important outcomes of CarbonNext and contents an overview about the different evaluation steps – from the identification of convenient, unconventional carbon sources to the specifications of a production route. The synthesis pathways and products were analysed in respect to economic and environmental aspects. Furthermore, soft topics like social acceptance were investigated: How can a strategic transfer of knowledge lead to increase awareness for e.g. CO_2-based products look like? The final outcomes of the project are concrete examples for possible applications with considered locations for the use of unconventional carbon sources, chosen based on the above mentioned criteria in specific determined scenarios. The analysis from evaluating available unconventional carbon sources to the production of economical and environmental feasible production routes is also logically structured by the Work packages investigated in CarbonNext. Thus, the following report presents the results of the Deliverables in the sequence of their delivery number, and, as mentioned above, summarizes the results with so-called best practice examples.

Overview of work package results

1.1 Mapping unconventional carbon sources

1.1.1 Map of all relevant CO_2 and CO containing gases

Carbon monoxide (CO_2) and carbon dioxide (CO) are formed from the combustion of carbon containing materials. The carbon in the gases can be used as a feedstock for the process industry replacing carbon from fossil sources. As we move into a more carbon constrained environment, the ability to re-use carbon molecules multiple times could become a key component in the drive to reduce carbon emissions and ensure the sustainability of the process industry. The identification of the most promising sources of these carbon emissions enables new and existing industries to identify symbiotic opportunities which could enhance deployment. The processes where CO_2 or CO can be used in the process industry rely technologically and economically on several factors, including the volume and purity of the source and its proximity to suitable infrastructure.

The European Pollutant Release and Transfer Register (E-PRTR) is a Europe-wide register that provides key environmental data from industrial facilities in European Union Member States and in Iceland, Liechtenstein, Norway, Serbia and Switzerland. The register contains data reported annually by more than 30,000 industrial facilities covering 65 economic activities across Europe. The E-PRTR data set used (2014) lists facilities with CO_2 emissions above 0.1 Mt per year; total emissions of CO_2 in Europe from these facilities amounted to 1,779 Mt in 2014. There are many facilities with emissions below 0.1 Mt per annum, but it is unlikely that capturing the emissions from these facilities for use in the process industry will be economically viable. The E-PRTR database shows that there is a wide range of CO_2 sources across Europe producing more than sufficient CO_2 emissions to meet the demand that could be utilised as a feedstock for the chemical industry. The major inhibiting factor in CO_2 capture from point sources is the energy required for the capture and separation processes. The energy needed will both affect the cost and environmental implications of the process. Therefore, targeting the purest streams of CO_2 will keep energy requirements to a minimum, as smaller volumes of emitted gas will need to be processed to result in the same volume of purified CO_2 when compared with a more dilute source. Primary targets for sourcing CO_2 should focus on those sources with the highest concentration of CO_2, (Hydrogen production, natural gas processing, ethylene oxide manufacture and ammonia production) as the higher concentration of CO_2 reduces the cost of capture. However, larger volumes of CO_2 are available from the iron and steel industry and cement industries, albeit at lower CO_2 concentration. As industries look to decarbonise (particularly the iron and steel and cement sectors) there is an observed market pull to deploy CO_2 utilisation technologies to provide an economically beneficial method of reducing CO_2 emissions. As next-generation carbon capture technologies reach the market, other sources of CO_2 may become increasingly economically viable.

Carbon monoxide (CO) is produced if the combustion of carbon containing sources to CO_2 proceeds under a lack of oxygen resulting in an incomplete combustion reaction. Diffuse industrial CO emissions originate from internal combustion engines in urban areas and point sources from various industrial sectors release CO. CO emissions higher than 0.005 Mt have to be reported in the E-PRTR.

The total CO emission for all European countries in 2014 was 3.38 Mt. Germany, followed by UK, France, Spain and Poland were the main emitting countries. The main contributor to CO emissions is the metal sector which contributes 71% (2.40 Mt), followed by the construction sector at 11% (0.37 Mt), the chemical sector at 10% (0.34 Mt), and the energy sector at 6% (0.20 Mt). The main emissions within the metal sector come from the manufacture of basic steel and ferro-alloys accounting for 92% of the metal sector emissions (2.2 Mt).

The amount of CO emitted is not equivalent to the amount produced in a steel mill, much more is produced than is emitted. Typically, CO and other gas-by-products from integrated steel mills are either re-used in the steel production process for on-site heating processes or for electricity production, only a minor fraction is emitted. This means a large proportion of the electricity and steam required in the steel production process is produced from steel mill gases. However, it is now being considered whether converting this CO into carbon-based products would be more beneficial than using it for electricity or steam production. The potential amount of CO available could be higher by a factor of 12-20, if the CO which is currently used for electricity and stream production was also taken into account.

In the work package, different maps have been created to analyse the availability of CO_2 and CO and their distance to a potential consumer (in this case chemical parks). Figure 1 depicts all 2014 registered point sources of CO and CO_2 over Europe. Further maps in the deliverable highlight important aspects and an online map on https://carbonnext-eu.github.io/ allows for an interactive analysis by the user.

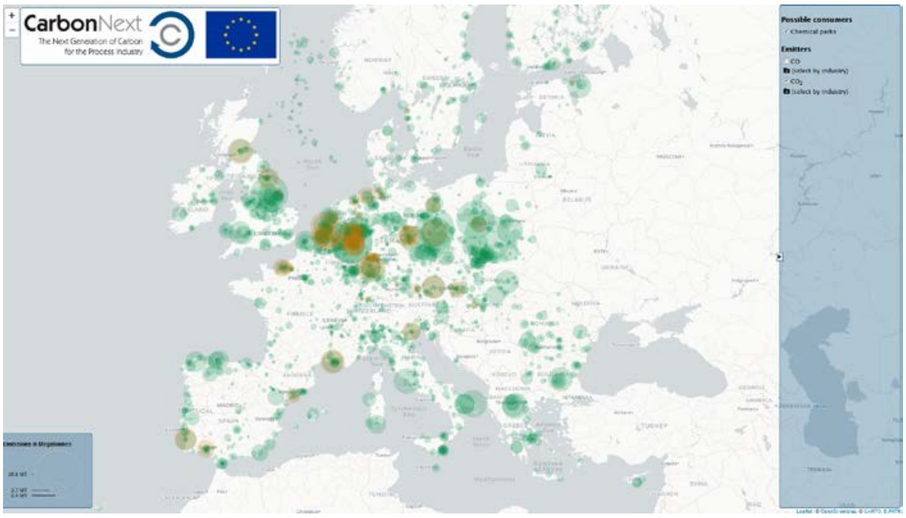

Figure 1: Online map of CO and CO_2 point sources in Europe

The map is the basis for the identification of promising locations where CCU applications have the best conditions for successful employment.

1.1.2 Shale gas

CarbonNext concluded that, compared to North America and Asia-Pacific, the technically recoverable resources of shale gas in Europe are rather small. The production of shale gas has several challenges, not least undetermined environmental risks and the related lack of political support. Furthermore, drilling results so far has been poor in some of the most promising regions.

A significant number of countries have imposed a moratorium on shale gas production until they can better assess the risks. Poland was estimated to have the largest resources in Europe, but tests were disappointing and regulatory issues led many companies to move their activities elsewhere. The United Kingdom has given concessions to start shale gas production, despite strong opposition. This shale gas would be used mainly for national consumption and is not likely to be exported to the continent. If substantial amounts of especially ethane are found in the shale exploitation, this could give the UK chemical industry an advantage over continental producers. Thus, it is therefore unclear yet how shale gas will develop in Europe, but a gas revolution as was seen in the United States is very unlikely to occur. Outside of the UK, where there is a chance it could have an impact on domestic industry, we do not foresee that shale gas will have an impact on Europe’s processing industry and CarbonNext disregarded it from further research.

1.1.3 Other non-conventional natural carbon sources

According to the IEA, unconventional hydrocarbons are “any source of hydrocarbons that requires production technologies significantly different from those used in currently exploited reservoirs”, while recognizing the imprecision and time dependence of this definition.

The conclusion of this project is that unconventional hydrocarbon resources in Europe will not play a significant role in the future as the availability is expected to be small. For example, there are only 13 proven crude oil reserves in Europe compared to 226 in the US. Similarly, heavy oil reserves in Europe are a small fraction of the total reserves in the World. In the project, several production challenges including significant capital investment, environmental issues such as those related to fracking, risk of gas explosions, large water demands and water contamination for coal-bed methane as well as a need for stable conditions in terms of pressure and temperature which requires a large amount of resources have been identified.

It is concluded that the environmental concerns surrounding the utilisation of these unconventional carbon sources are high and that their potential is very low. The project partners of CarbonNext therefore do not foresee that these sources will have a significant impact upon Europe’s processing industries and therefore those carbon sources have been disregarded from further research.

The conclusion of Work package 1 is that Carbon dioxide and carbon monoxide are promising alternative carbon sources that are available in significant amounts, and thus, can theoretically substitute a significant amount of fossil carbon sources as feedstock in the process industry in Europe.

As more carbon from CO/CO_2 is available than it is currently demanded, sources with a high concentration of CO_2 where capturing processes are simple and in comparison cheap are of greater interest that large volume producers with lower concentration.

The following CO_2 sources will be used as preferred sources for the best practice examples:

- Hydrogen production
- Natural gas processing
- Ethyle oxide manufacture
- Ammonia production

CO from steel production seems to be another promising alternative carbon source for the processing industries. In a next stage it must be evaluated further if and how the steel industry could benefit from this alternative use of the CO.

More detailed information can be found in deliverable 1.1,1.2 and 1.3.

1.2 Value chains

1.2.1 Value chains

The CarbonNext-Team identified and summarised the most important chemical pathways where CO and/or CO_2 can be employed as chemical building block or feedstock. It was identified which potential products can be synthesised from CO_2 and CO, which routes and processes can be utilised to produce these products.

The information gathered is based upon the scientific literature plus other published reports, company websites and various news sources.

In order to ease the evaluation of the differing potential products that can be made from CO_2 and CO, the products have been places into the following four separate sections

- **Chemicals** – mostly liquids and gases for utilisation by the chemicals, pharmaceuticals and plastics industries
- **Chemicals/Fuels** – products which can be utilised as a chemical or a fuel (e.g. ethanol)
- **Fuels** – products whose use is almost exclusively as a fuel
- **Solid Materials** – e.g. construction aggregates

With these groupings, the products have been further classified into chemical families, such as organic acids, olefins, polyols etc. so that similar products can be grouped together and an example product given where multiple are possible. Information about the potential products, the nature of the chemical reactions which create them and the development status of the reactions are provided as text in each of the four sections listed above in CarbonNext's Deliverable 2.1.

For the selection of all the possible pathways CarbonNext looked at volume of the market and value of the market, including import and export for products that can be made from CO and/or CO_2. The analysis is based upon the Eurostat database. Prodcom (Eurostat's system for the collection and dissemination of statistics on the production of goods) – sold production, exports and imports by PRODCOM list (NACE Rev. 2) – annual data (DS-066341) for 2016 was used to obtain the quantities (tonnages) of the conventionally-produced chemicals produced within or imported into, the EU28 countries. The quantity imported was added to the quantity of production sold to obtain information of the scale of the market available. If the export quantity had been subtracted, this would have provided a measure of the level of consumption within the EU28. However, this was not done because by leaving the exports in the figures, the overall quantity of CO_2 which could be incorporated into products by EU manufacturers and the overall size of that market available can be appreciated.

In total, **43 product** were described, which can be produced from CO_2, utilising 71 different routes of synthesis. Similarly, **22 products** which can be produced from CO were described, along with the 33 different chemical routes from which they can be synthesised.

The information provided in this report, together with that provided in the review of industrial symbiosis submitted as deliverable 2.2, will be utilised to enable a selection of the most favourable products to be made. This selection will be based upon market data, environmental impacts and potential symbiotic interactions between industries and will be presented as deliverable 2.3.

The full list of products and synthesis pathways can be found in CarbonNext's Deliverable 2.2.

1.2.2 Industrial symbiosis

The main idea of industrial symbiosis is the collaboration of different industry sectors and branches, in which materials, energy, water and by-products as well as wastes are exchanged in order to use the outcome streams of one industry as input for another at local level. It is an over the fence of enterprises approach, where – in an ideal world - all industry partners in a region interconnect in the best way possible in order to generate as little as possible waste and uses only the amount of energy that is absolutely necessary. Thus, the demands of society for resource savings and environmental protection can be addressed in a new and united approach.

At the moment, flue gas streams such as CO_2 and/or CO containing gases are not used in large scale industrial symbiosis undertakings, apart from Urea production which is symbiotic with ammonia production. As CO_2 and CO can be seen as an important carbon source for the process industry in order to replace fossils like oil and gas for the production of organic chemicals, the capture of CO_2 emitted by e.g. the steel, cement, or calcium carbonate industry followed by selling it to a nearby chemical company would expand the framework of industrial symbiosis. Thus, industrial symbiosis has the potential and the technological possibilities for the re-use of gaseous waste streams, in particular CO_2 and CO containing steams to become part of the concept. In CarbonNext, possible liaisons between industries sectors in respect to CO_2/CO utilization were summarized. Especially the steel industry is involved in different promising funded research projects with the goal to capture the CO_2-emissions linked to the steel manufacturing process and hand it over to demanding chemical industries that eagerly seek for opportunities to substitute fossil carbon sources for the synthesis of various organic chemicals – including balk and specialty chemicals.

The implementation of such processes can be highly sophisticated, because of well established processes where various side-products must be taken into account in order to observe which kind of products may depend on the current set-up or if actually new by-products could be unlocked.

As shown in AP1, the most relevant sources of CO_2 related **only** to mass for further usage of carbon in other sectors are from steel manufacturing, cement industry and chemicals production (Please note that it was concluded in WP1 that firstly high concentrated sources of CO_2 are higher in the usage hierarchy). The most relevant amount of CO can be obtained from steel manufacturing. A link between those emitters with the chemical industry is a way to serve carbon based synthesis with carbon from flue gases.

The most prominent examples within the analysis in respect to CO_2/CO utilisation is the linkage of steel manufacturing with chemicals production. Two very large cooperation projects are funded under this topic, the Steelanol and Carbon2Chem project. Figure 2depicts the multilayer pathway options of using carbon from the steel sector the processing of chemicals on the basis of the Carbon2Chem initiative. Those large products underline the importance and potential of coupling these two sectors. Further symbiotic effects could be exploited by linking CO_2 outputs of chemical sites with the production of new chemicals. Activities at Rotterdam Harbour Industrial complex can be taken as examples. Linking CO_2 streams from chemical production to agriculture is currently implemented in the Netherlands by distributing waste CO_2 via distribution network from Rotterdam Harbour Industrial park to greenhouses all over the country. Finally, the potential of coupling CO_2 originated by bioprocesses with chemical or biochemical production has been investigated. Most important is CO_2 coming from digestion processes. The main pathway here is methanation to produce SNG. Further approaches focus on the production of agricultural fertiliser.

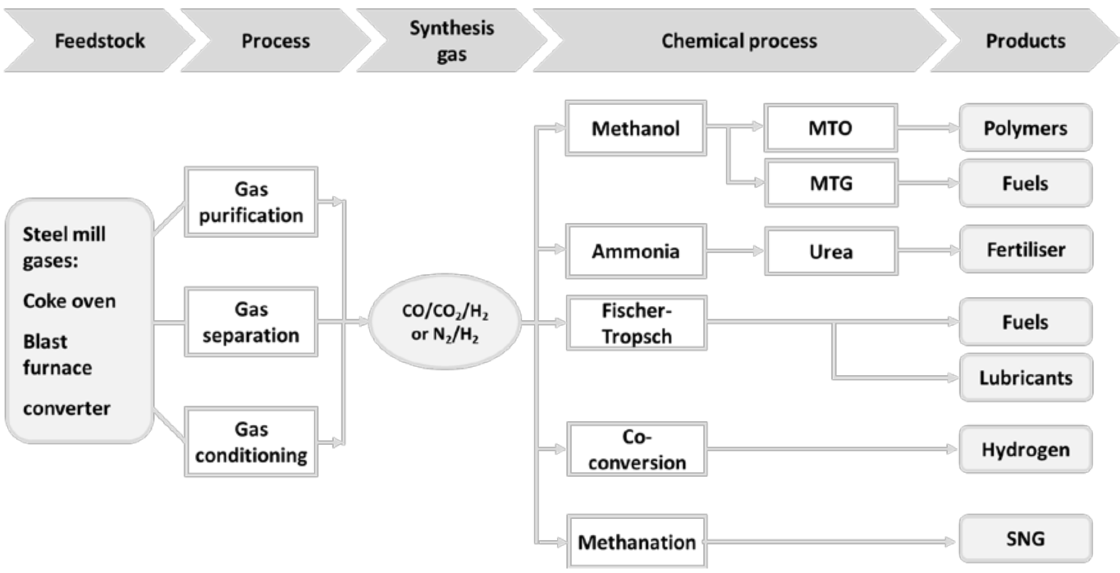

Figure 2: Carbon2Chem approach (adapted from Carbon2Chem®)

Future looking concepts and further potential symbiotic relationships can be employed by using the outcome of the deliverable 2.1 and 2.2, showing the products that can be produced and placing the production an industrial environment with most possible advantages in respect of heat management and feedstock supply. Large companies or SMEs may use the deliverable as checklist in order to identify gaps and business cases that can be installed in industrial parks in order to use CO_2 or CO streams, which are otherwise vented to the atmosphere. IP ownership as well as revenue questions must be considered and well-defined while exploring new symbiotic relationships.

1.2.3 Pre-selection of the most relevant processes

A methodology was developed in order to pre-select the most promising processes and products for further investigation, as a rough filter can already help to limit the products and synthesis routes to those that have a clear potential for implementation in short and middle term. E.g. synthesis pathways that are currently estimated with a low TRL (1- 3) are not mature enough that any deeper evaluation about the economic and environmental potential can generate reliable information.

The products are selected together with the route(s) used to synthesise those products from CO_2 and CO. The selection is made from the lists of products identified in the deliverable 2.1 Value Chains.

Selection can be based on various scientific questions. **The main goal for CarbonNext was to select products which will enable the replacement of fossil-derived carbon used in the European process industries by 2030.** To select products and routes which would achieve this aim, it was decided that:

- the CO/CO_2 utilisation process must have a high technology readiness level (TRL) to ensure that uptake by 2030 is possible,
- the market value of the products needs to be significant,
- the CO/CO_2 utilisation potential needs to be significant to ensure that the amount of fossil-sourced carbon being replaced is worthwhile,
- the products should not require other non-catalytic chemical inputs which contain fossil-sourced carbon, as this would limit the impact of utilising the alternative carbon source.

The selection was carried out by assessing these four criteria for each product/route using a qualitative approach (i.e. ranking them as high, medium or low) and choosing the products which had a combination of the most favourable traits. Table 1 shows the indicators used for the pre-selection and the ranking levels.

Table 1: Ranking of the indicators used to select the routes which have the best traits to replace fossil-derived carbon by 2030. Higher rankings (red) are less desirable than lower rankings (green).

	Ranking		
Indicators	**3**	**2**	**1**
TRL	1 - 3	4 - 6	7 - 9
Market value	<1 €b/yr	1 - 10 €b/yr	>10 €b/yr
CO/CO_2 utilisation potential	<1 Mt/yr	1 - 10 Mt/yr	>10 Mt/yr
Other sources of fossil carbon in the product	Yes and it cannot be made from CO or CO_2	Yes, but it can be made from CO or CO_2	No

Fourteen products were selected for further analysis, nine of which can be synthesised from CO_2 or from CO: **ethylene, propylene, benzene, xylene, methanol, dimethyl ether, gasoline, diesel fuel and methane**. In addition, **1,3-butadiene, dimethyl carbonate, ethanol and kerosene-type jetfuel** were selected from those produced from CO and ethylene carbonate from those synthesised from CO_2.

While researching process, economic and environmental data for those processes, it was decided to group them as shown in Table 2. We also included Calcium carbonate for comparison purposes.

Table 2: Selected products and their most common use

CO	CO_2	Olefins (Ethylene, Proylene) – for PE plastics, detergents, antifreeze	Chemicals
CO	CO_2	Aromatics (Benzene, Xylene) – for PET plastics, polystyrene and other	
	CO_2	Ethylene carbonate – as solvent or Li-Ion electrolyte	
CO		1,3-Butadiene – for rubber, tyres, seals	
CO		Dimethyl carbonate – fors solvents and polycarbonate plastics	
CO		Ethanol – medical, fuel and solvent use	Chemicals or fuels
CO	CO_2	Methanol – as feedstock for formaldehyde (plastics) or fuel replacement	
CO	CO_2	Dimethyl ether (DME) – for organic synthesis, solvents or fuel replacement	
CO	CO_2	Fischer Tropsch fuels – gasoline or diesel replacement	Fuels
CO	CO_2	MTG Gasoline	
CO	CO_2	Methane	

The technology readiness level of each route of synthesis was provided, based upon the published literature or estimated from the description of commercial activity. The market for the majority of the products was provided in terms of the total tonnage of product currently produced and sold and imported into the EU, together with the unit value and total value of this market. In addition to the market values, the amount of CO_2 or CO utilised per tonne of product was provided, together with the total mass of CO_2 or CO assuming the total EU market is met by that production route. Finally, the requirement for H_2 per tonne of product was provided together with a list of the other non-catalytic inputs required by the chemical reaction.

1.3 Framework conditions

1.3.1 CO_2 and CO availability and price analysis

In order to conduct an economic assessment for the most promising pathways, it was assessed what are the conditions under which it is interesting to use CO/CO_2 in the process industry. Figure 3 shows the parameters that are important for a CO_2 and CO availability and price analysis.

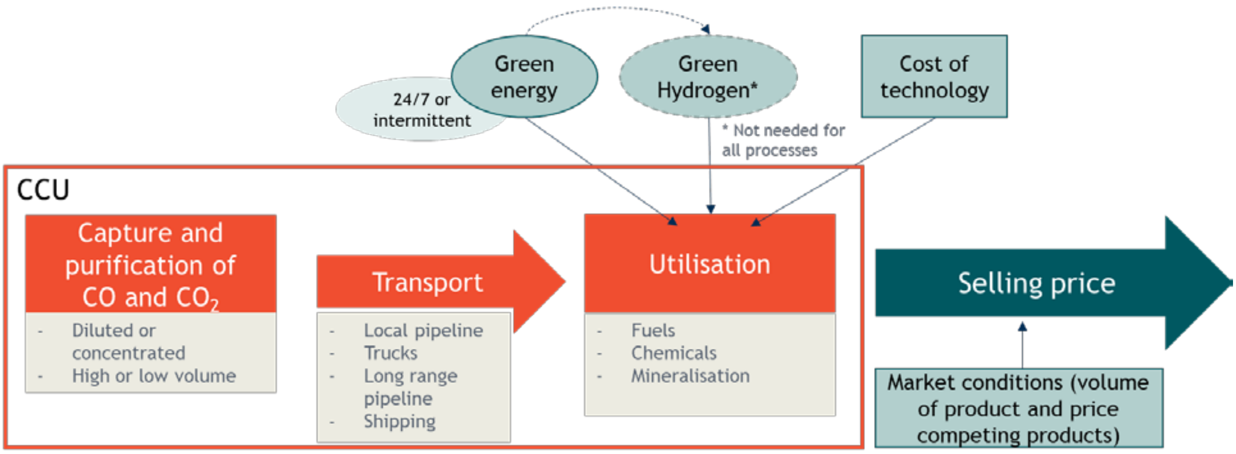

Figure 3: Scope of the CCU business case

For CO_2 utilization, this was done by assessing current and forecasted CO_2 emission prices under the EU-ETS and the costs of carbon capture and transport. In the case of CO utilization, CO_2 emission prices were subtracted from the gains from electricity generation using CO to assess at what CO_2 emission price CO use for electricity generation would be discouraged. In respect to CO_2 and CO sources, it was evaluated which type of point sources will most likely have volumetrically smaller or higher flue gas streams.

Without considering the product price, utilization of neither CO_2 nor CO in the process industry is attractive under the present ETS and electricity prices. In the case of CO_2 utilization, CCU would need to be included in the ETS scope and the minimum ETS price of emission allowances should reach ~ 35 EUR/tCO_2 in order for investors in CCU to get a positive input in the business case. This price could be attained by 2030 in a low-price scenario and in an optimistic scenario the emission allowances could be as high as 75 EUR/tCO_2. In the case of CO utilization, it has been calculated that a CO_2 price of around 38 EUR/t CO_2eq would be needed to make the case interesting. As such it is unlikely that CO utilisation as feedstock in the chemical industry will become attractive before at least 2030.

It is important to highlight that our assessment does not take into account initial up-front investments in the carbon capture and transport technologies. For example, costs of building new pipelines for transport have not been taken into account.

1.3.2 Acceptance and Awareness of CO_2 Utilisation

The readiness of a new technology is not the only factor that determines the success of a market launch. In the past, it was often seen that not unreserved acceptance and the lack of awareness can be a fatal hurdle for a product or process. Thus, for a successful implementation of CCU and CO utilisation pathway it is wise to analyse where and why might be pitfalls, and if those threats are not justified, how it can be argued against those concerns.

Carbon Dioxide Utilisation (CO_2 utilisation or CDU) is a group of emerging technologies that uses CO_2 as a carbon resource to make products. The growth in the CO_2 utilisation technologies is primarily driven by industry and investors looking for new renewable feedstocks, in conjunction with searching for methods to reduce emissions. However, a wider variety of external stakeholders are interested in CO_2 utilisation. Key stakeholders can include policy makers, non-governmental organisations (NGOs), large and small companies, investors and the general public. It is vital to understand the background and motivation for a specific stakeholder's engagement with CO_2 utilisation; as this can help frame discussions and provide an understanding for their motivation. Key motivations can include reducing CO_2 emissions to the atmosphere, interest in buying products or new business opportunities that are perceived as being greener.

CO_2 utilisation is not a single simple process; it is a whole suite of technologies that utilize carbon dioxide as a resource to make new products. Therefore, creating an effective communication strategy is important and can present unforeseen issues. Research into understanding the acceptance and awareness of CO_2 utilisation process is still in its infancy with only a few published studies available. As more studies are published and more CO_2-derived products are established in the market, both the understanding of how to develop effective communication strategies along with general awareness of the field will evolve.

It is recommended that when communicating about new CO_2 utilisation products the interests and motivations of the stakeholders are carefully considered from the start. Furthermore, there are a range of considerations and misconceptions that should be taken into account when deciding on communication strategies for CO_2 utilisation. In general, it is simpler to convey a single product or product group rather than discuss the whole range of CO_2 utilisation technologies. Careful consideration should be given to explain that the product is made from carbon from CO_2, its properties and the amount of CO_2 emissions that are avoided by manufacturing the product from CO_2. By taking into account these considerations it is hoped that commonly observed pitfalls can be avoided. The following figure shows simplified the avoidance CO_2 emissions by using CO_2 base synthetic fuels. Such easy to understand figures shall help to explain the main concept of the replacement of fossil carbon through carbon from CO_2 or CO.

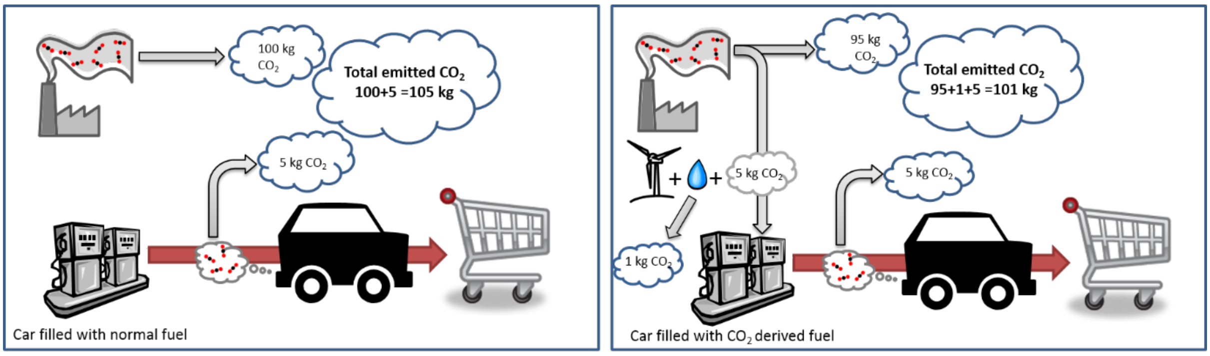

Figure 4: Simplified representation of avoided CO_2 in fuel use. NB this representation does not include the small amount of emissions resulting from carbon capture. (Armstrong et al., 2015)

1.3.3 Risk impact register

The risk impact register presents a list of disruptive factors and the impacts that these may have upon carbon dioxide (CO_2) utilisation. The focus is upon the utilisation of CO_2 as carbon monoxide (CO) is already widely used in industry as a chemical feedstock and as an energy source.

The disruptive factors are split into those arising from technology, policy or public perception. Such disruptive factors, together with their resulting impacts, have the potential to alter the risks associated with CO_2 utilisation technologies, or the products made using those technologies. The impacts may be beneficial, for example by helping the business case for investment, or they may have adverse impacts which limit the market for CO_2-derived products or make production more expensive and so the products less competitive. The register assigns an overall probability of occurrence for each impact, together with the significance of the impacts. Finally, an impact rating is calculated from the probability of that impact occurring and its significance.

The report concludes that CO_2-derived transport fuel replacements have particular risks due to the potential for significant contraction of the market due to multiple disruptive technologies, policies and public acceptance. Potential investors in CO_2-derived fossil fuel replacements need to balance such risks. Mention is made of the public discontent over plastic waste making its way into the oceans. This issue was not assessed at this time to be as highly significant, but with the several of the selected chemicals used as inputs into the polymer industries, such issues need to be watched. Finally, the risk posed by rises in electricity prices is common to the majority of CO_2 utilisation technologies, but will be felt most acutely by those also needing to generate renewable hydrogen as part of the production process. The selected technologies which do not require additional H_2 sources include those produced via gas fermentation technologies (depending upon the precise process used), which includes 1,3-butadiene and ethanol. Methanol produced using a high temperature solid oxide cell does also not require the addition of externally supplied H_2 as it effectively makes its own from the water used in the process. However, it is not known at this stage whether this process is any more efficient than using standard water electrolysis to produce the required H_2.

1.4 Economic and environmental impacts of most promising CCU pathways

1.4.1 Methodology to assess the business case and economic potential of CCU

The goal of the methodology is to define the scope of the CCU business case and provide a general framework, identifying and briefly describing the key market conditions which are required for a successful CCU business case. Three (climate policy) scenarios and related assumptions which have an impact on the business case assessment were defined.

Framework to assess the CCU business case

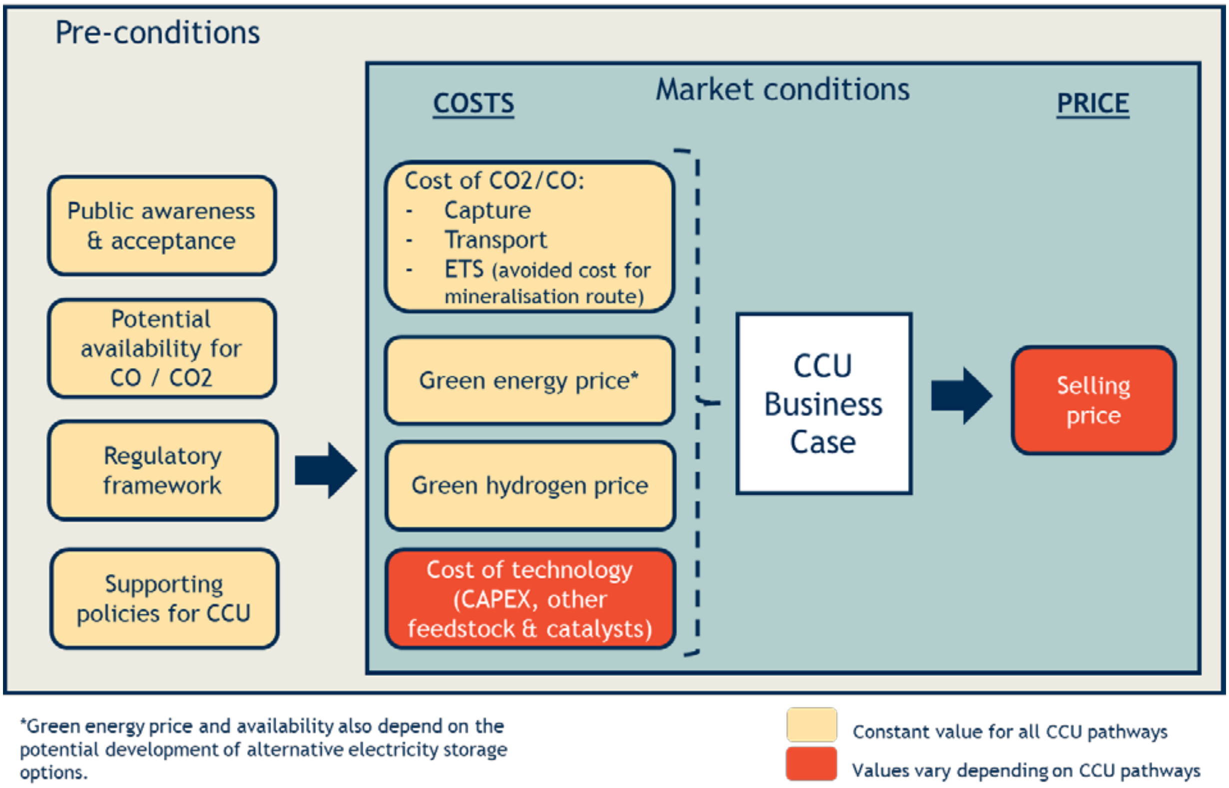

Figure 5: Methodology to assess the business case and economic potential of CCU

Pre-conditions are those which need to be in place for CCU to be a feasible option, and are further discussed in other reports within this project. For more details, please refer to deliverable 3.2 for public awareness and acceptance and to deliverable 1.1 for potential availability of CO and CO_2. The regulatory framework has a big impact on the market conditions. Important policies that might impact the business case are for example the EU Emissions Trading System (EU ETS), the renewable energy directive, the biofuels directive and car emissions regulations, but also research, development and innovation support. Policies directly supporting CCU would also strongly impact the business case.

Market conditions, on the other hand, are those which have an impact on the CCU costs and the CCU product price. These market conditions can be dependent or not on the selected pathways. Basically, the costs are split into cost of technology and operational costs. Cost of technology is hard to estimate due to the lack of comparable industrial size installations, but CAPEX will be derived from similar technologies. Operational costs were reduced to energy and hydrogen input and cost of CO_2/CO because of their relative importance for the energy intensive processes. Those operational costs were treated in scenarios to tackle the wide range of possible developments especially for the price of green electricity and hydrogen.

Each of the selected pathways (see chapter 1.2.3) was broken down into processes, and for each process, an inventory analysis was established, focussing on the main energy inputs (electricity, hydrogen and heat), CO and CO_2 input and greenhouse gas emissions. Those processes were then assembled in the pathways in a material flow analysis, paying attention that the temperature and pressure levels of the output of one process correspond to the input level of the next process.

The material flow analysis leads to a sum of CAPEX, energy, hydrogen, CO and CO_2 inputs for each pathway. Combined with each of the price scenarios, a cost to produce the product can be obtained. This cost does not include all OPEX or a profit margin and is therefore not directly comparable to the current market price. The comparison is therefore meant to be informative only: it will show how much higher or lower the CCU pathway production costs are compared to the selling price of fossil-based alternatives, which will give an indication of how competitive the pathway would be under each scenario.

1.4.2 Methodology to assess the environmental impact and energy efficiency of CCU

The goal of this task was to compare the selected routes from deliverable 2.3 in terms of GHG emissions. All pathways were compared with each other and with their respective conventional route. As the purpose of the CO/CO_2 utilization products is to replace a conventionally produced product, the analysis can be limited to a cradle-to-gate analysis. This means that only the production of the product was compared. Product combustion and characteristics, use as well as end-of-life phase were considered to be identical. As this is a screening study, the main focus was on the main energy and material inputs. All smaller inputs, especially catalysts, but also plant lifecycle, were mentioned where available, but it was outside the scope of this study to include a detailed LCA on them. This is deemed acceptable as the quantities of those inputs are very low. Nonetheless, they might have important environmental impacts as some of them include rare metals or complicated production steps. This should be included in a further analysis if a particular pathway is to be considered for deployment. In all cases, this study did not produce comprehensive LCAs. LCAs are product and location specific. Therefore, whilst this approach of screening can be used to eliminate the most inefficient pathways it cannot replace a full LCA. A full LCA, not just carbon foot-printing, would need to be carried out to draw conclusions on deploying a specific pathway in a specific circumstance. However, this LCA would be carried out at a much later stage and in the first instance a screening will give the desired outcomes to enable selection between pathways.

The investigated processes use CO or CO_2 as a carbon source to replace predominantly fossil carbon in chemicals or fuels. Both are emitted from a process (e.g. steel mills for CO or ammonia production for CO2). A full LCA would do a system expansion to include this process in the system boundaries to account for changes in the process or interdependencies. For example, the full functional unit of a steel mill with a CO utilizing process would be 1 kg of product + x kWh of electricity + y kg of steel (because the CO is currently used in an internal power plant to generate electricity). As we are doing a preliminary screening study to compare CO and CO2 pathways, we wanted to have a functional unit of 1 kg of product where possible. Therefore, we introduced the concept of GHG credits and burdens for the process depending on the use of CO_2 and CO. In the simple case of CO_2 usage, a credit of 1 kg CO_2-eq per kg CO_2 used and a burden for the capture and conditioning are assumed.

Similar to the economic analysis, scenarios were implemented for the uncertain future supply of energy, hydrogen, CO_2 and CO. Those are supposed to show the carbon intensity of those inputs depending on the share of renewable energy available.

The material flow analysis was then used in the same way as before to calculate Greenhouse Gas (GHG) emissions (with a focus on CO_2, as other GHG emissions are hard to obtain for technologies with low TRL) from the cumulated list of inputs and outputs for a pathway and the scenarios.

For each pathway, a reference was defined. This reference was treated in the same way as the CO/CO_2 utilization process, especially using the same scenarios for the GHG intensity of energy and hydrogen inputs.

The result is a GHG emissions value for each pathway and each reference for all scenarios. This allows for a comparison of the pathway with its reference and a comparison of pathways with the same product among each other. A comparison of pathways with different products is not trivial, as criteria have to be defined. Examples are GHG savings per unit of renewable electricity, GHG savings per kg of product, or absolute GHG emissions per kg of product, either in a certain scenario or in the best case.

1.4.3 Economic and environmental impacts of most promising CCU pathways

CAPEX and GHG emissions for the processes were gathered and combined with costs and GHG emissions for the main energy inputs (electricity, hydrogen and heat), CO and CO_2 inputs from scenarios. The scenarios account for the uncertainty of future supply of those inputs and are summarized below.

Table 2: Cost scenarios for main inputs

	High e- and H_2 price	Low e-price and high H_2 price	High e-price and low H_2 price	Low e- and H_2-price
H_2 price [€/kg H_2]	6,000	6,000	2,000	2,000
Electricity price[€/kWh]	0,140	0,059	0,140	0,059
Heat price [€/kWh]	0,060	0,030	0,060	0,030
CO_2 price [€/kg CO_2-eq]	0,045	0,022	0,045	0,022
CO_2 ETS [€/kg CO_2-eq]	0,032	0,032	0,075	0,075
CO price [€/kg CO]	0,010	0,010	0,006	0,006

Table 3: GHG emission scenarios for main inputs

GHG emissions	EU Mix	RES ~ 30%	RES ~ 80%	Decarbonized
Electricity [kg CO_2eq/kWh]	0,44	0,15	0,06	0,01
H_2 [kg CO_2eq/kg H_2]	10,70	7,58	2,14	0,67
Heat [kg CO_2eq/kWh]	0,26	0,16	0,04	0,01
CO_2 supply [kg CO_2eq/kg CO_2]	-0,85	-0,77	-0,94	-0,98
CO supply [kg CO_2eq/kg CO]	-0,75	-1,29	-1,46	-1,55

This way, a price and GHG emissions were obtained for each scenario. The price only includes CAPEX and OPEX related to the main inputs. For a full business case, several costs like human resources, catalysts, etc. are needed. Additionally, the production cost can be substantially lower than the selling price: some of the products can have margins of up to 25%.

These prices and GHG emissions were compared to a conventional (fossil based) reference pathway producing the same product. Reference data was obtained from databases ecoInvent and PRODCOM and adapted by using the energy prices and GHG emissions for the inputs in the scenarios.

As costs for these CO and CO_2 based products do not include all OPEX costs and margins, the comparison is meant to be informative only: it will show how much higher or lower the CO and CO_2 based product costs are compared to the selling price of fossil-based alternatives, which will give an indication of how competitive the pathway would be under each scenario.

It was found that the differences between the pathways can be quite big, but in most cases strongly depend on the scenario assumptions and the first conversion steps (especially from CO_2 to syngas). Also, uncertainties are in the same order of magnitude as the differences between the pathways because of literature sources using different methodologies and result presentations, but also because of uncertain technological developments. Keeping that in mind, it can still be said that:

(1) With some exceptions, CO and CO_2 based pathways are more expensive than the reference, even in the most favourable scenario.
(2) From CO_2, Ethylene carbonate, DME, Methane, Ethylene, propylene are the most competitive pathways
(3) From CO, Ethanol, 1,3-butadiene, DME, DMC are the most competitive
(4) To emit less GHG, electricity and hydrogen used in the processes need to be produced from at least 50 to 80 % renewable energies
(5) From CO_2, FT fuels, Dimethyl ether, Methanol, Aromatics, MTG gasoline, olefins allow for the highest GHG savings in the most favourable scenario.
(6) From CO, DMC, DME, FT fuels, Ethanol, 1,3-butadiene allow for the highest GHG savings in the most favourable scenario.

To allow stakeholders to use their own data or scenarios, an Excel tool was built. It contains the inventory analysis based on literature sources, the pathways and scenario assumptions and some analysis tools. It is a custom tool that is not self-explanatory, but allows to build on the current analysis by changing parameters quite easily. The results of the Excel tool can then be imported into an online visualisation tool that can help extract information from the wealth of scenario and syngas route options. Results can be filtered by any criteria.

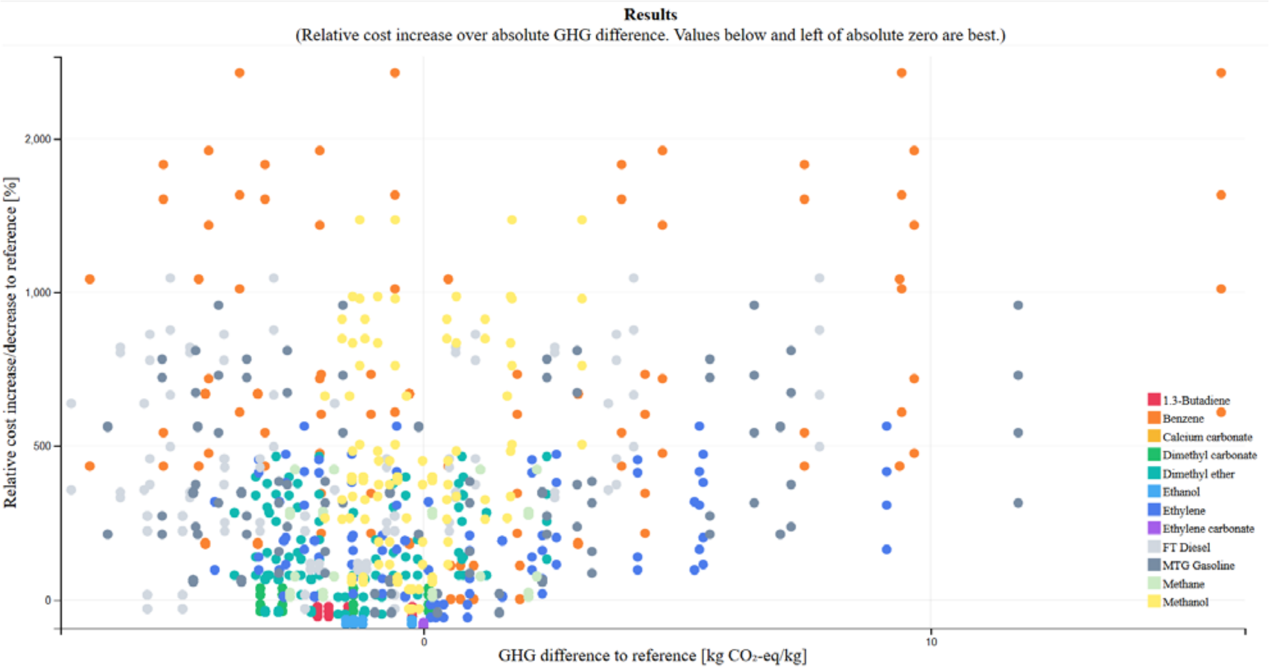

Figure 6: Overview costs and greenhouse gas emissions for selected pathways (use the tool)

Results to the bottom left are best. As stated above, Ethanol, 1,3-butadiene and DMC can all be found in that corner. Depending on the scenario and syngas assumptions, other pathways like e.g. FT fuels also allow for GHG emission reductions at low costs.

Conclusion

The results of CarbonNext show in the first place that there are numerous options for the process industry to use carbon from flue gases containing CO_2 and CO to substitute carbon from fossils for the synthesis of organic chemicals. The volume of CO_2/CO available from (very) pure sources can likely cover the demand largely for CCU till 2030. Also the less pure sources from some processing industries (like Steel and Cement) is likely to last for many decades to come. While capturing processes will hopefully become more efficient, also those sources can serve as carbon input for the process industry in high quantities.

The economic analysis depicts that from CO_2/CO derived products are currently more expensive in comparison to established fossil carbon based products. Especially the high extra cost for (renewable) energy, the high cost for green Hydrogen and the high cost from intermittent availability of green energy is causing substantial differences with the current market price. It was clear that pathways starting with CO were much more favourable then those starting with CO_2 (due to lower energy needs). Production cost will most likely decrease while technologies will be further developed and the costs for renewable energy will likely decrease as well. But even substantial price drops will likely not be enough and other measures are required to make CCU price competitive with fossil.

The GHG analysis shows that considerable GHG savings are possible, but strongly dependent on the energy inputs and the first process steps, especially the production of hydrogen and syngas. When using only renewable energy and an efficient conversion route, all pathways can save GHG emissions compared to the conventional reference, but compared to other ways of using the renewable energy, they might save less GHG.

The analysis focussed on list of most relevant bulk chemicals chosen in CarbonNext. However, other chemical products with higher margins, such as fine chemicals, can be the key to unlock the whole potential of CCU pathways as those products are in a higher price category and the CCU has less impact on the overall product-costs / margins.

CarbonNext recommends supporting more investigations of the products and synthesis ways introduced in the economic and environmental analysis as well as on fundamental research, development of pilot and demonstration projects, and further projects that evaluate the potential of CO_2 and CO as feedstock for the process industry. The project has shown first conclusions; however, while the field is growing, more detailed and reliable assessments must be conducted.

Carbon mineralisation products were not assessed as part of this process although they have great potential. However, this was out of scope of our project as explained in chapter 1. Nevertheless, the consortium believes that carbon mineralisation can play an import role to lower CO_2 net emissions from industry in the future.

The outcomes of CarbonNext are tools as building blocks for further assessments of CCU processes that can be used by industry (especially SMEs), academia and also by policy makers. The CarbonNext methodologies provide specific but flexible tools to assess to match CO_2/CO sources with

CCU process opportunities, and tools to calculate GHG results and economic projections of all kind of chemical pathways where the users can introduce their own variables and scenarios. In the long term, those evaluations will help to develop strategies for setting up promising business cases.

Proposal of how the tools can be used

(1) Map with pure CO_2 or CO and chemical parks in Europe

Figure 7 is a screenshot of our online mapping tool and shows chemical parks in orange. The size of the circle corresponds to the available CO_2 emissions in a radius of 5 km.

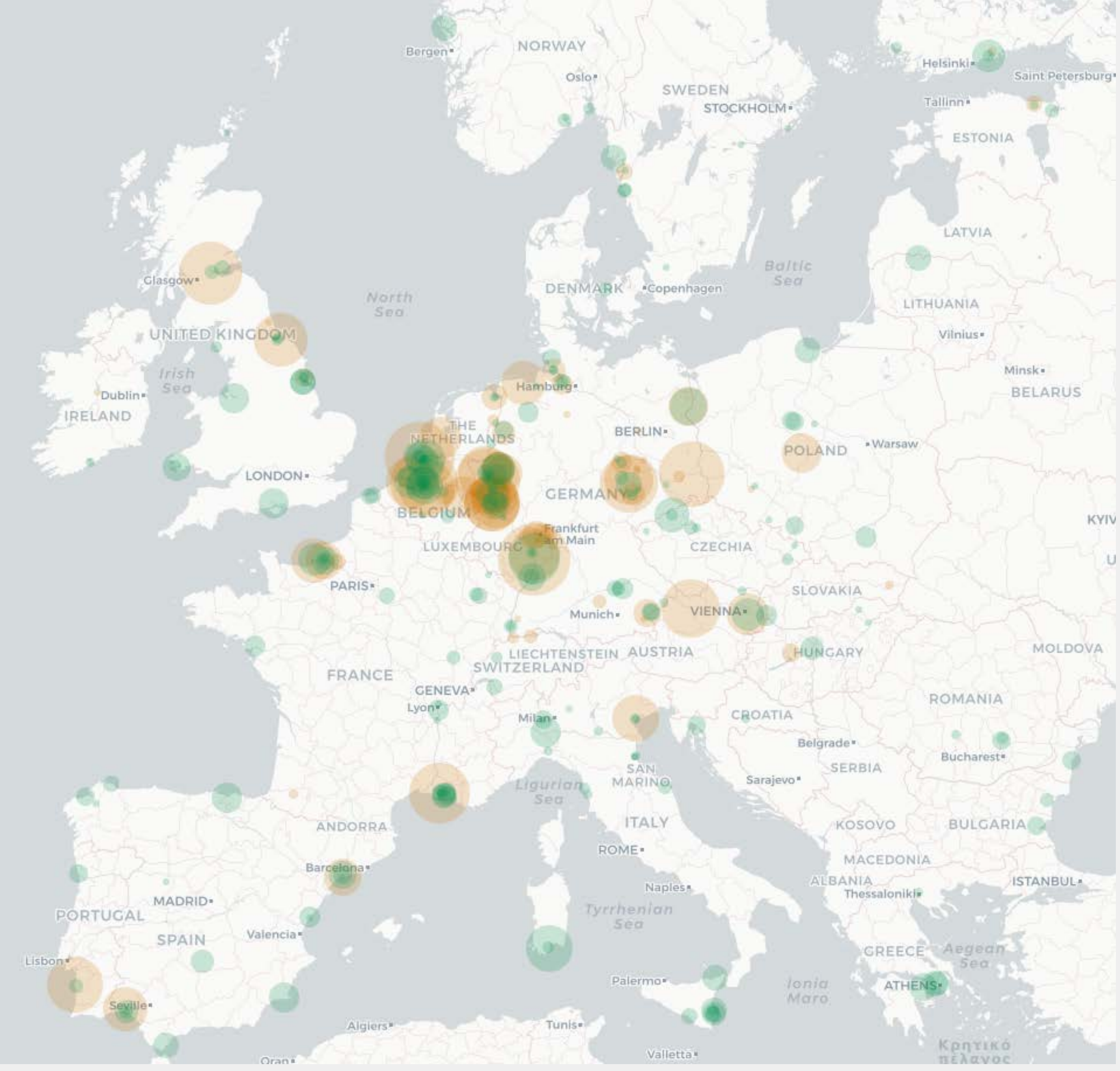

Figure 7: Map with chemical parks (orange) and highly concentrated CO_2 sources (green)

This allows for example to obtain a list of chemical parks with over 1 Mt of concentrated CO_2 available in a radius under 5 km:

- ZILS - Sines Industrial and Logistics Zone, Portugal (from refinery)
- Fos-Lavera-Berre, France (from plastics and precursors, refinery, cracking)

- Ludwigshafen, Germany (from steam cracking and others)
- Dormagen, Germany (from ammonia and other chemicals)
- Lülsdorf, Germany (from refinery)
- Marl, Germany (from chemicals)
- Terneuzen, Netherlands (from steel, cracking and chemicals)
- Antwerp, Belgium (from chemicals, refinery and fertilizers)
- Rotterdam, (Netherlands (from refinery)
- Leuna, Germany (from refinery)
- Schwedt, Germany (from refinery)
- Schwechat, Austria (from refinery)
- Middlesborough, UK (from chemicals and refinery)
- ChemCoast park, Germany (from ammonia and chemicals)

(2) Select interesting pathways from our list by adapting the weighting of the selection criteria

Our selection tool contains a structured list of products and pathways to produce those products from CO_2 and CO with criteria such as TRL, market size and market value, CO_2 utilisation potential and reaction details (enthalpy, pressure, temperature and inputs) and a tool to sort those pathways depending on a weighting of each criteria. Each stakeholder can use this tool to find pathways matching her criteria.

(3) Techno-economic-environmental analysis

The basis of the economic and environmental analysis is an Excel tool that contains input-output and process data for each process used in the analyzed pathways, as well as literature sources. It then combines those processes to pathways and derives costs and GHG emissions for each pathway in each scenario. Even if the tool is not intended to be used by stakeholders, it could be used in follow-up projects, either as a data source or as a basis for a more detailed analysis.

(4) Visualization of the techno-economic-environmental analysis

The visualisation tool is a graphical way of exploring the results. To make the number of scenarios, pathways and syngas routes manageable, the user can interactively choose the ones that seem important and get a graph of costs and GHG emissions.

(5) Combine all tools to find geographical, economic and environmental “sweet spots”

Once a location is selected like shown in the first bullet point, it is possible to narrow down the list of pathways by the size of the plant and the criteria from bullet point (2). This list can then be analysed under energy and cost scenarios matching the regional conditions and the time frame with the visualization tool from (4).

Example of how the tools could be used

As an example, when taking a closer look at the last park, we can see that the emissions are occurring in the same chemical park and seem to be at least partially highly concentrated CO_2 emissions from an ammonia plant.

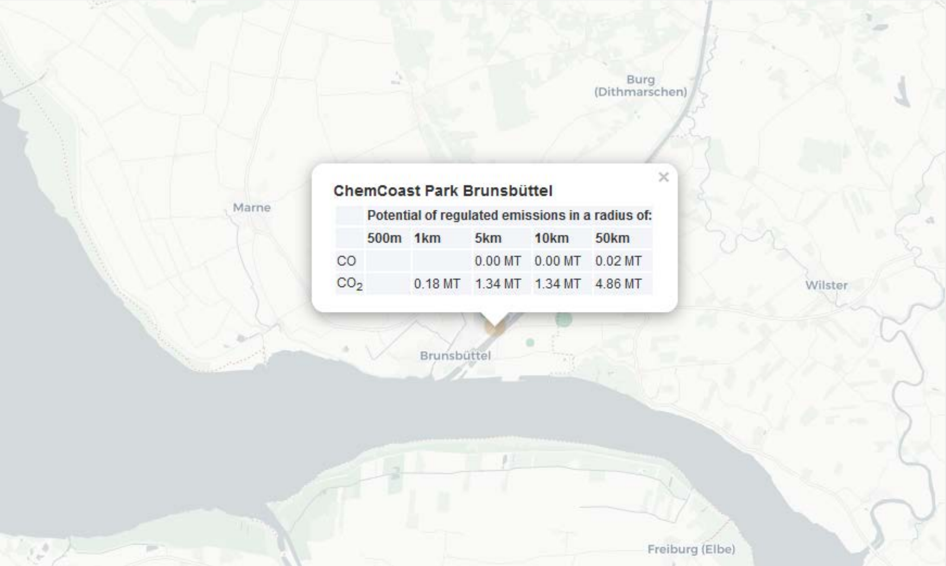

Figure 8: Chemical park Brunsbüttel with an ammonia plant with pure CO_2 emissions. Near Heide, 40 km north, there is also a refinery with additional 0,97 Mt CO_2 emissions.

For most pathways, relevant amounts of renewable electricity are needed. Luckily, the region has vast amounts of wind energy and even surplus electricity that currently cannot be transported to regions that could use the electricity. The map below shows the wind turbines in the region. Ongoing discussions on new electricity transport lines could be avoided by using the electricity locally.

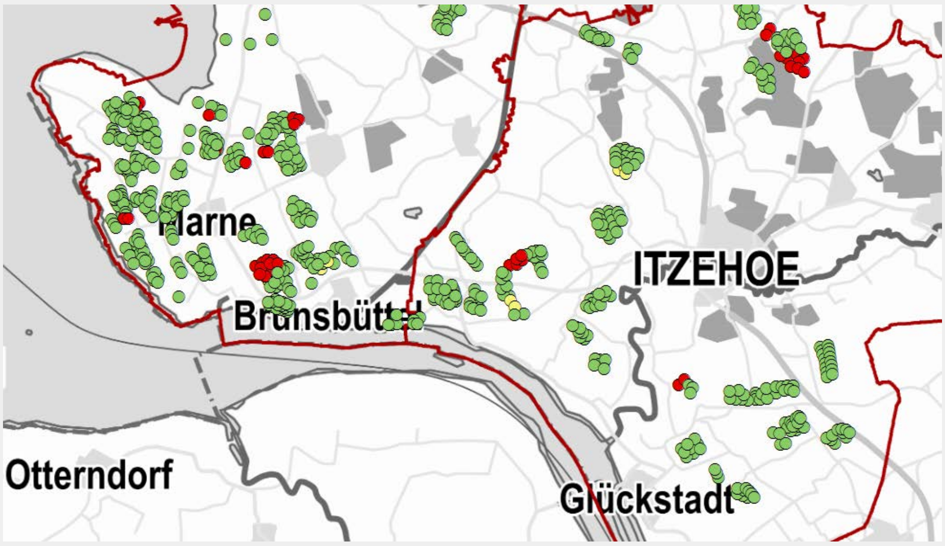

Figure 9: Wind turbines in the Brunsbüttel region (green: in operation).
Source: https://www.schleswig-holstein.de/DE/Fachinhalte/W/windenergie/Downloads/Windeignungsgebiete.pdf?__blob=publicationFile&v=12

From (2), with our uniform weighting, we obtained the list described in chapter 1.2.3.

We could exclude pathways that do not match the availability of roughly 1 Mt CO_2, but we assume that most pathways from CO_2 could scale to that size.

In the next step, we would limit the results to CO_2 based pathways and a high renewable energy share (80 % or above) as well as a low electricity price. We would also exclude syngas routes from fossil methane as they are not compatible with the goal of the example. We would then obtain a chart like the following.

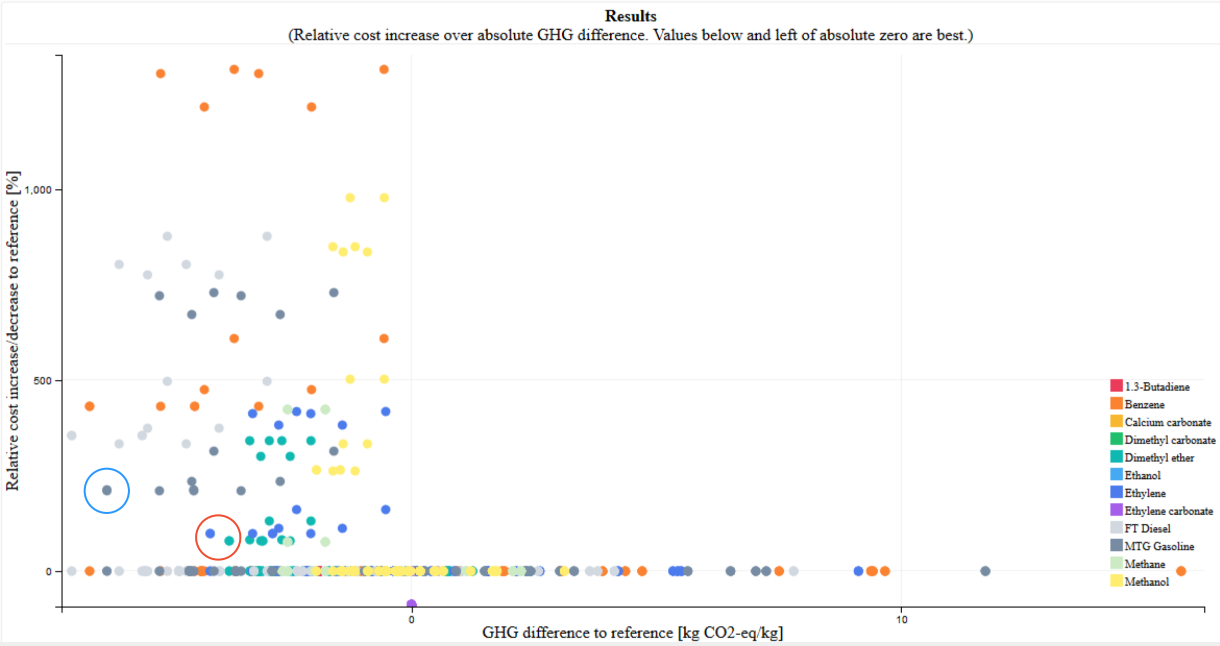

Figure 10: filtered chart from the example

We could decide that Ethylene or DME allow for the highest GHG savings at the lowest costs (see red circle), or look at MTG gasoline as a way to reduce GHG emissions even more (blue circle).

The focus of CarbonNext was on bulk chemicals as those large volume products promise to utilize highest amounts of CO_2 or CO. Fine chemicals, that will probably be more and sooner cost competitive can be seen as low hanging fruits that will show that CCU processes are profitable and thus, other players will be encouraged to synthesis further products.